The Ability of Men's Lacrosse Helmets to Reduce the Dynamic Impact Response for Different Striking Techniques in Women's Field Lacrosse

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Background: Women's field lacrosse is described as a noncontact game relying primarily on rules to decrease the risk of head injuries. Despite not allowing head contact, however, concussions continue to be reported in women's field lacrosse.

Purpose: To assess the ability of men's lacrosse helmets to decrease linear and angular acceleration for different striking techniques in women's field lacrosse.

Study Design: Controlled laboratory study.

Methods: A helmeted and unhelmeted Hybrid III 50th Percentile headform was attached to a Hybrid III neckform and were subjected to impacts by 8 striking techniques. Eleven athletic females completed 5 slashing techniques, while physical reconstruction equipment was used to simulate falls and shoulder and ball impacts to the head. Three trials were conducted for each condition, and peak resultant linear and angular accelerations of the headform were measured.

Results: Falls produced the highest linear and angular acceleration, followed by ball and high-velocity stick impacts. Low-velocity stick impacts were found to produce the lowest linear and angular accelerations. Men's lacrosse helmets significantly decreased linear and angular accelerations in all conditions, while unhelmeted impacts were associated with high accelerations.

Conclusion: If women's field lacrosse is played within the rules, only falls were found to produce high linear and angular acceleration. However, ball and high-velocity stick impacts were found to produce high linear and angular accelerations. These linear and angular accelerations were found to be within the ranges reported for concussion. When the game is not played within the rules, men's lacrosse helmets provide an effective method of reducing linear and angular accelerations. Thus, women's field lacrosse may be able to reduce the occurrence of high linear and angular acceleration impacts by having governing bodies improving rules, implementing the use of helmets, or both.

Clinical Relevance: Identifying striking techniques that produce high linear and angular acceleration specific to women's lacrosse and measuring the capacity of a men's lacrosse helmet to reduce linear and angular acceleration.

Keywords: concussion; women's field lacrosse; biomechanics of brain injury; injury prevention

Head injuries are among the most serious injuries in sports. It is estimated that 1.6 million to 3.8 million concussions occur as a direct result of participation in athletics.[12,13] In the United States, participation in female lacrosse has increased at the youth, high school, and collegiate levels, with a 10-year growth rate of 219% reported in 2008.[2] With such growth in popularity, attention must be brought to the game to ensure athletes can compete safely.

Women's field lacrosse is considered a noncontact game with little mandatory protective equipment, other than eyewear and a mouth guard. The sport primarily relies on rules and sportsmanship to minimize head injuries. The style of the game and enforcement of the rules is intended to protect players from head injuries. Despite women's field lacrosse being noncontact, however, concussions continue to be an issue.[24,42] The concussion rate in women's lacrosse has been reported to be the second highest in women's sports, with women's soccer reporting the highest rate of concussions.[24] Injuries in women's lacrosse occur as a result of player-equipment contact, player-player contact, and player–playing surface contact.[24] Because of limitations in the current rules and the protective ability of equipment, the use of headgear may be beneficial.

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Considerable debate continues around the use of protective headgear in women's lacrosse and the possible implications of added protective equipment.[6,7,15,17,18,21,23,28] Some have observed that due to the strict noncontact rules, it makes the use of helmets and other protective gear unnecessary.[17] In addition, Goldenberg and Hossler[15] noted that despite the high rate of head and face injuries observed in their study, there was a lack of severity in these injuries, which led them to conclude that helmet use was not necessary. However, several studies encourage the use of protective head/face gear in women's lacrosse.[6,23,28] Such recommendations have been based on comparing the mechanisms of concussion in women's and men's lacrosse.

Women lacrosse players have been found to have higher rates of head injuries and have reported similar concussion rates compared with men.[6,18,24,42] The women's and men's game are considerably different, and the nature of the injuries varies dramatically by sex.[18] In men's field lacrosse, player-to-player contact is the most common mechanism of concussion (0.31/1000 athlete exposures [AEs]),[23] followed by player-to-stick contact (0.02/1000 AEs)[23] and player-to-ball contact (0.02/1000 AEs).[6,8,22-24] In women's lacrosse, the primary mechanism of concussion is either stick (0.12/1000 AEs)[23] or ball contact (0.12/1000 AEs).[2,6,7,18,23,24,28] Because there is a smaller percentage of player-to-stick contact and player-to-ball contact causing concussion in men's lacrosse and a larger percentage of player-to-stick and player-to-ball impacts causing head injuries in women's lacrosse, using helmets may decrease the rate of concussion in women's lacrosse. To date, no study has assessed the ability of men's lacrosse helmets to reduce linear and angular acceleration in women's lacrosse. The purpose of this study was to assess the ability of men's lacrosse helmets to decrease linear and angular acceleration for different striking techniques in women's field lacrosse. We hypothesized that each striking technique would produce unique linear and angular acceleration responses, and a men's field lacrosse helmet would decrease the linear and angular accelerations experienced by the headform.

METHODS

A helmeted and unhelmeted Hybrid III 50th Percentile headform and neckform (Humanetics) was subjected to impacts by participants and physical reconstruction equipment. The Hybrid III headform (mean ± standard error of measurement [SEM]: mass, 4.54 ± 0.01 kg) was attached to a Hybrid III neckform (mean ± SEM: mass, 1.54 ± 0.01 kg). Nine calibrated single-axis accelerometers (model 7264C-2KTZ-2-300; Endevco) were fixed in an orthogonal position near the center of gravity of the headform using the "3-2-2-2" array developed to measure and calculate 3-dimensional motion during an impact.[29] Peak linear and angular accelerations were then used to assess the risk of sustaining a concussion. The protocol was reviewed and approved by the University of Ottawa Office of Research Ethics and Integrity (H06-12-23). Data are reported as mean ± SD unless otherwise indicated.

Participants

Eleven athletic women representing a postcollegiate population (weight, 63.1 ± 12.0 kg; height, 1.65 ± 0.08 m; age, 29.2 ± 3.9 years) were recruited for this study. Two of the participants had over 15 years of lacrosse experience, and the remaining participants were novice lacrosse players but athletic. All participants were healthy women who took part in a minimum of 150 minutes of sport-related physical activity a week and had no pain or discomfort from past injuries to the upper limbs or shoulders.

Lacrosse Equipment

Participants were given 1 of 2 commercially available lacrosse sticks to carry out the slashing trials: a women's lacrosse stick with an STX aluminum shaft and an STX Level head (STX; mean ± SEM: length, 1.090 ± 0.001 m; mass, 0.34 ± 0.03 kg) and a lacrosse stick with a titanium shaft and a Brine Edge head (Brine; length, 1.045 ± 0.001 m; mass, 0.40 ± 0.03 kg). A lacrosse stick with a titanium shaft was used, as there was a concern that an aluminum shaft would break as a result of higher energy impact. A single commercially available warrior lacrosse ball (Warrior; mean ± SEM: mass, 0.153 ± 0.001 kg; diameter, 0.064 ± 0.001 m; stiffness, 628.2 ± 33.5 N/cm)[4] that met the Canadian Lacrosse Association (CLA) specifications was used during the ball-impact trials. In the helmeted condition, the headform was fitted with a commercially available Cascade Pro7 (Cascade) lacrosse helmet, certified by the National Operating Committee on Standards for Athletic Equipment (NOCSAE) DOC (ND) 041-11m12. A men's lacrosse helmet was used since they are currently the only lacrosse helmet that meet certification standards.

Procedures

A helmeted and unhelmeted headform were subjected to impacts by 8 striking techniques at the front and the side of the headform to reflect the most common locations struck in women's lacrosse.[2] Three trials were conducted for each condition.

Informed consent was obtained for all participants. Video clips of the desired striking technique (1-handed, 2-handed, and follow-through slashing) were shown before testing to ensure participants understood what was required. Pilot testing revealed experienced and novice lacrosse players did not produce significantly different linear and angular accelerations from striking techniques. Preliminary data are available in the Appendix (available online at http://ajsm.sagepub.com/supplemental). The participants were allowed to warm up and stretch before beginning and were instructed to take 6 or more practice trials until they were comfortable with the striking techniques. Each participant was instructed to strike the target location on the headform using the shaft of the lacrosse stick. The location on the shaft that struck the headform was between 0.578 ± 0.001 m and 0.560 ± 0.001 m from the bottom of the shaft. A 0.050 ± 0.001-m wide marker was placed on the shaft of the lacrosse stick to ensure

the same point was used to impact the headform for each trial. The desired impact locations on the headform were marked with an "X," and the target was 0.04 ± 0.001 m by 0.04 ± 0.001 m. If the impact was off target or the technique was improper, the trial was excluded and the participant was asked to complete the trial again. Review of high-speed video determined if the impact hit the marked target and proper technique was used. During participant striking, the headform and neckform were attached to a sliding table that was set to a maximum achievable height of 1.48 m.

Five participants (weight, 64.9 ± 17.7 kg; height, 1.59 ± 0.05 m; age, 29.4 ± 1.8 years) were instructed to complete 1-handed and 2-handed slashing using a correct stick checking technique that represented low-energy impacts. This technique involves a snapping motion of the wrist as described by US Lacrosse. In the 1-handed slash condition, participants gripped the lacrosse stick with 1 hand at the bottom of the shaft. The participants struck the headform as they would in a typical game situation. The inbound velocity was 6.6 ± 3.7 m/s. In the 2-handed slash condition, participants were instructed to grip the stick with 2 hands as they would in a game situation when stick checking. The participant then struck the headform with an inbound velocity of 7.5 ± 3.4 m/s. For both 1-handed and 2-handed slashing, the location of the target on the side of the head was defined as 0.080 ± 0.001 m above the right intersection of the coronal and transverse planes (Figure 1, A and B). The location of the target on the front was defined as 0.060 ± 0.001 m above the anterior intersection of the midsagittal and transverse planes (Figure 1, A and B). These impact sites were chosen to better reflect the typical location of impact from proper stick checking technique.

Six participants (weight, 62.0 ± 4.8 kg; height, 1.69 ± 0.08 m; age, 29.8 ± 4.7 years) were instructed to modify the 2-handed stick checking technique. Moderate impacts were completed by slashing using the elbow extensors, and severe impacts were simulated using the shoulder and elbow muscles. The inbound velocities for moderate and severe 2-handed slashing were 8.0 ± 2.0 m/s and 10.4 ± 2.2 m/s, respectively. The locations of the target during the moderate and severe 2-handed slashing were defined as the right intersection of the coronal and transverse planes and 3.50 ± 0.0 cm above the anterior intersection of the midsagittal and transverse planes (Figure 1, C and D). These impact sites were chosen to reflect stick impacts directed toward the head.

Five novice lacrosse participants (weight, 56.1 ± 3.4 kg; height, 1.63 ± 0.07 m; age, 29.8 ± 5.3 years) completed follow-through slashing. Participants were instructed to grip the stick as they would in a game situation when shooting and strike as if they were taking their hardest shot. Participants were allowed to take a step into the impact to simulate a game situation for accuracy. The inbound velocity was 10.3 ± 2.3 m/s. These are with a range of 9.8 to 15.4 m/s for stick shaft velocities during shooting of female lacrosse players at a skill ranging from high school to college variety.[5] Impacts were directed to locations seen in Figure 1C and 1D.

An air canon was used to simulate player-to-ball contact. The canon consists of the same support/piston frame and table housing the Hybrid III headform as the pneumatic linear impactor. A lacrosse ball (mass, 0.14 ± 0.01 kg) was loaded into the air cannon with a length of 0.700 ± 0.001 m and a diameter of 0.065 ± 0.001 m, which was designed to launch baseballs. A lacrosse ball has a diameter of 0.064 ± 0.001 m and thus is smaller than a baseball. To launch the lacrosse ball from the air cannon, a cloth was used to create a seal between the ball and the inside diameter of the cannon. The lacrosse ball was released with an inbound velocity of 28.3 ± 2.2 m/s. Such a velocity was selected as the ball can travel up to 60 mph (26.8 m/s) in the women's game.[23] The impacts were to the locations seen in Figure 1A and 1B. These locations were used to simulate a player attempting to avoid the ball after inadvertently being within the shooting space.

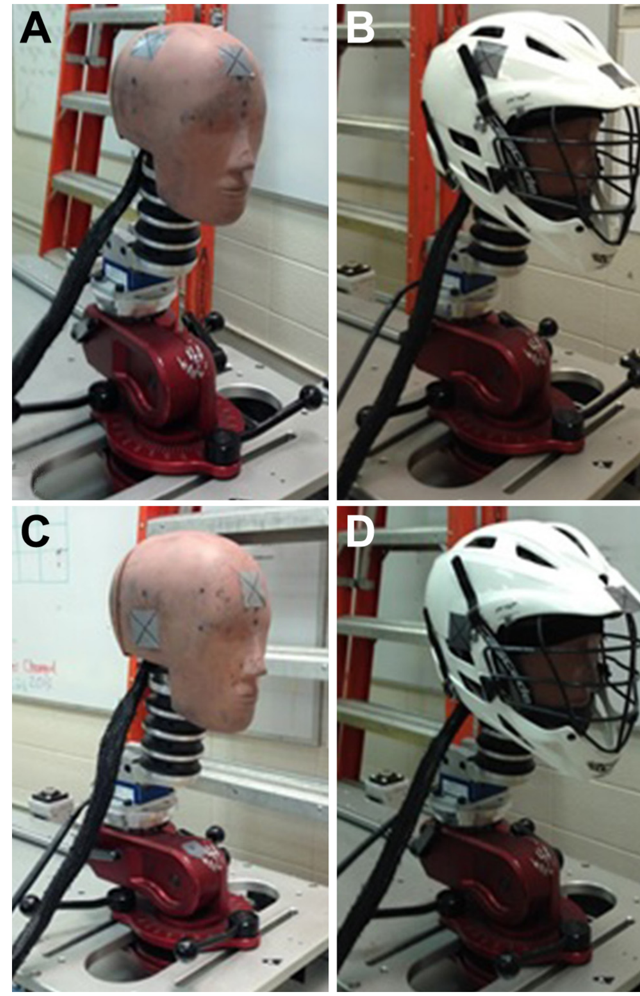

Figure 1. (A, B) Unhelmeted and helmeted headform for legal play and ball impacts. (C, D) Unhelmeted and helmeted headform for aggressive play and follow-through slashing. The ''X'' on the headform and helmet marks the target locations.

A pneumatic linear impactor was used to simulate the shoulder-to-head contact. The impactor consists of 3 major components: the support/piston frame, the impacting arm, and the table housing the Hybrid III headform. The frame

supports the impacting arm, the compressed air canister, and the piston. The pneumatic piston is fired via an electronically controlled solenoid with the air supplied from the compressed air canister, which propels the impacting arm (mass, 13.1 ± 0.1 kg) toward the headform. The end of the impacting arm was fitted with a cap consisting of 67.79 ± 0.01 mm of R338 vinyl nitile (VN) foam. The Hybrid III headform and neckform were attached to a sliding table to allow for postimpact movement. The impacts were to the side, center of gravity, and 0.060 ± 0.001 m above the anterior intersection of the midsagittal and transverse planes. The inbound velocity of the impact was 5.0 m/s in accordance with high-speed running of female soccer players.[20,26] This velocity was chosen as it represents the velocity at which females run while playing competitive sport. These impacts were used to reflect impacts seen while a player is attempting to retrieve a loose ball and collides with an opponent.

A monorail drop rig was used to simulate the head impacting the playing surface. The monorail drop system was used with a modular elastomer programmer (MEP) anvil to simulate the playing surface. The Hybrid III headform (mass, 4.54 ± 0.01 kg) and neckform (mass, 1.54 ± 0.01 kg) were attached to the monorail drop rig and impacted at an inbound velocity of 4.5 m/s. This velocity was selected to simulate a head impact velocity determined by Mathematical Dynamic Models (MADYMO) of a 1.57-m female pushed forward at 1.0 m/s. The locations of the impact were the front impact site in accordance with NOCSAE lacrosse helmet certification and the side center of gravity.

Data Collection and Filtering

All participant striking and ball impact trials were recorded with a Fastcam 512 PCI high-speed video camera (High Speed Imaging). Video data were collected at 2000 Hz and analyzed via Photron Motion Tools software to determine inbound velocity of the lacrosse stick and lacrosse ball. Signals from the 9 accelerometers were collected at 20 KHz by a TDAS Pro Lab system (DTS) and filtered through a 1650-Hz low pass Butterworth filter using the Society of Automotive Engineers (SAE) J211 Class 1000 protocol (SAE, 2007).

Analysis

The peak acceleration values were taken for both linear and angular acceleration and averaged across each participant. Individual peak values for each participant were also examined. To compare striking techniques, data were separated by impact location, and 1-way analyses of variance (ANOVAs) with the independent variables of striking technique were used to analyze peak linear and angular acceleration. Post hoc Tukey tests were then used to compare differences among the 8 striking techniques. Data were then separated by striking technique and location. Independent sample t tests were used to compare helmeted and unhelmeted trials for the dependent variables of peak linear and angular acceleration. The probability of making a type I error for all comparisons was set at $\alpha = 0.05$. All data analyses were performed using the statistical software package SPSS 19.0 for Windows (SPSS Inc).

TABLE 1
Effects of a Helmet on the Dynamic Response of the Headform

		P Value	
Striking Technique	Location	Linear Acceleration	Angular Acceleration
1-handed slash	Front	.132	.230
	Side	.167	.024
2-handed slash	Front	.056	.669
	Side	.017	.033
Moderate 2-handed slash	Front	.007	.185
	Side	.001	.002
Severe 2-handed slash	Front	.000	.034
	Side	.011	.048
Follow-through slash	Front	.001	.001
	Side	.003	.026
Shoulder	Front	.044	.925
	Side	.001	.654
Ball	Front	.014	.009
	Side	.010	.002
Fall	Front	.001	.001
	Side	.001	.001

RESULTS

Resulting peak linear and angular accelerations to an unhelmeted headform were significantly higher compared with a helmeted headform for moderate 2-handed slash, severe 2-handed slash, follow-through slash, shoulder collisions, ball impacts, and falls ($P < .05$) except for moderate 2-handed slash for front impacts (Figure 2 and Table 1). Peak linear and angular acceleration had no significant difference between an unhelmeted headform and a helmeted headform for 1- and 2-handed slashes ($P > .05$) except for peak angular acceleration for side impacts ($P < .05$) (Figure 2 and Table 1). Significant main effects of striking condition were found for both peak linear and angular accelerations across impact locations ($P < .001$). Fall and ball impacts were found to have significantly different peak linear and angular accelerations from all other striking techniques ($P < .05$) with the expectation of follow-through slash/ball for side impacts (Table 2). No significant difference for peak linear and angular accelerations was found between 1-handed slash, 2-handed slash, shoulder impacts, and moderate 2-handed slash ($P > .05$) except for 1-handed slash/moderate 2-handed slash with respect to linear accelerations produced during front impacts ($P < .05$) (Table 2). Follow-through slashing was found to produce significantly different peak linear and angular accelerations compared with 1-handed slash, 2-handed slash, moderate 2-handed slash, and shoulder impacts ($P < .05$) (Table 2). Follow-through slash and severe 2-handed slash were found not to be significantly different for peak linear and angular accelerations ($P > .05$) (Table 2). Severe 2-handed slashing resulted in

TABLE 2
Linear and Angular Acceleration *P* Values Comparing Striking Techniques

	P Value[a]			
	Linear Acceleration		Angular Acceleration	
Comparison	Front	Side	Front	Side
1-handed slash/2-handed slash	.999	>.999	>.999	>.999
1-handed slash/moderate 2-handed slash	.021	.45	.374	.468
1-handed slash/severe 2-handed slash	.001	.001	.001	.001
1-handed slash/follow-through slash	.001	.001	.001	.001
1-handed slash/shoulder	.647	.410	.986	.985
1-handed slash/fall	.001	.001	.001	.001
1-handed slash/ball	.001	.001	.001	.001
2-handed slash/moderate 2-handed slash	.099	.095	.635	.468
2-handed slash/severe 2-handed slash	.001	.001	.001	.001
2-handed slash/follow-through slash	.001	.001	.001	.001
2-handed slash/shoulder	.909	.574	.999	.985
2-handed slash/fall	.001	.001	.001	.001
2-handed slash/ball	.001	.001	.001	.001
Moderate 2-handed slash/severe 2-handed slash	.156	.074	.244	.033
Moderate 2-handed slash/follow-through slash	.001	.002	.001	.019
Moderate 2-handed slash/shoulder	.942	.999	.979	.991
Moderate 2-handed slash/fall	.001	.001	.001	.001
Moderate 2-handed slash/ball	.001	.001	.001	.001
Severe 2-handed slash/follow-through slash	.584	.914	.384	>.999
Severe 2-handed slash/shoulder	.031	.074	.083	.018
Severe 2-handed slash/fall	.001	.001	.001	.001
Severe 2-handed slash/ball	.001	.005	.001	.026
Follow-through slash/shoulder	.001	.005	.001	.011
Follow-through slash/fall	.001	.001	.001	.001
Follow-through slash/ball	.021	.100	.000	.056
Shoulder/fall	.001	.001	.001	.001
Shoulder/ball	.001	.001	.001	.001
Fall/ball	.001	.001	>.999	.001

[a]Post hoc Tukey test.

significantly different peak linear and angular accelerations compared with 1-handed slash, 2-handed slash, and shoulder impacts ($P < .05$) with the exception of severe 2-handed slash/shoulder for side impacts (Table 2). Moderate and severe 2-handed slashing did not produce slightly different peak linear and angular accelerations (Table 2). When the highest individual peak linear and angular accelerations produced by the 5 slashing techniques were assessed, it was found that moderate and severe 2-handed slashing and follow-through slashing were within the ranges reported for concussion (Figure 3).[14,21,25,27,30,33,41,43]

DISCUSSION

The purpose of this study was to assess the ability of men's lacrosse helmets to decrease linear and angular acceleration for different striking techniques in women's field lacrosse. The results revealed if women's lacrosse is played adhering to the rules, only falls produced high linear and rotational accelerations. However, if all risks associated with women's lacrosse are considered, ball and high-velocity stick impacts (moderate and 2-handed slashing and follow-through slashing) were found to produced high linear and angular accelerations. These accelerations were found to be within concussive levels as reported in the literature.[14,25,27,30,32,33,41,43] The results of this study demonstrated that when striking techniques were associated with high linear and rotational acceleration, men's lacrosse helmets significantly lowered the linear and angular acceleration. Although helmets have not been shown to prevent concussion, men's lacrosse helmets may provide an effective method to help reduce the risk of high peak linear and angular acceleration impacts in women's field lacrosse if one considers impact that occurs outside of the rules.

Both 1- and 2-handed slashing were found to produce low linear and angular accelerations. No significant differences were found between 1- and 2-handed slashing for peak linear and angular acceleration. Both striking techniques produced mean peak linear and angular accelerations below the range of concussion as reported in the literature when striking an unhelmeted headform.[14,25,27,30,32,33,41,43] Head injuries due to player-to-stick contact such as 1- and 2-handed slashing are more likely to result in a contusion than a concussion.[6,18,28] Therefore, if proper stick checking technique is adhered to, linear and angular

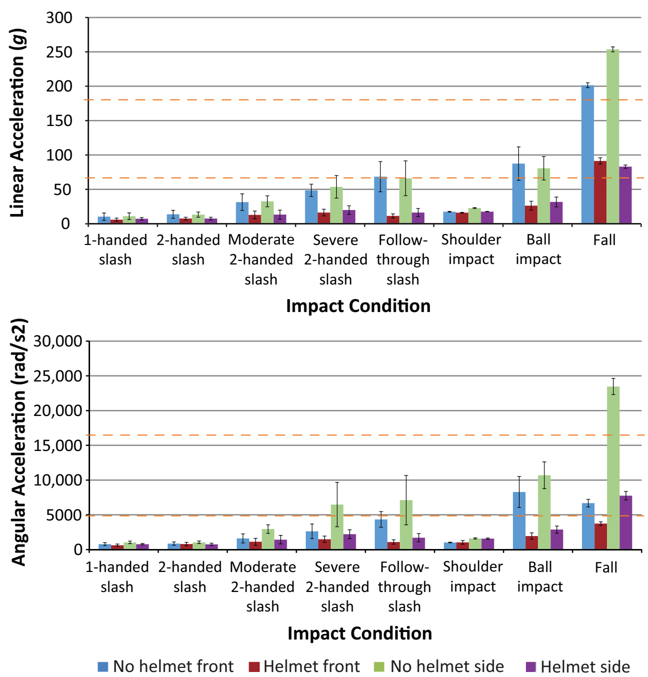

Figure 2. Mean peak linear and angular accelerations across all impact conditions. The dashed lines represent the range of reported concussions.[14,25,27,30,32,33,41,43]

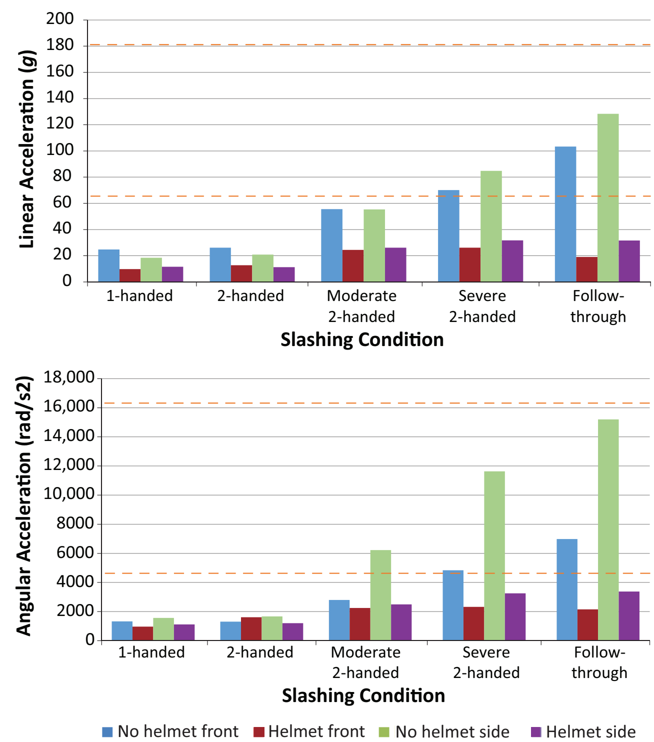

Figure 3. Individual peak linear and angular accelerations across slashing conditions. The dashed lines represent the range of reported concussions.[14,25,27,30,32,33,41,43]

accelerations experienced by the head are very low under these conditions.

However, player-to-stick contact is reported as a primary mechanism of head injury in women's lacrosse,[2,6,7,24,28] with studies reporting player-to-stick contact resulting more often in concussions than contusions.[7,16,23] The results of this study found that moderate 2-handed slashing did not produce significantly different mean peak linear and angular accelerations compared with 2-handed slashing, but severe 2-handed slashes produced significantly higher linear and angular accelerations compared with 1-handed slashing, 2-handed slashing, and moderate 2-handed slashing except for side impacts when comparing moderate and severe 2-handed slashing. Mean peak linear and angular accelerations produced by moderate and severe 2-handed slashing remained below reported ranges of concussion except for peak angular accelerations for side impacts to an unhelmeted headform, which were within the reported range of concussion.[14,25,27,30,32,33,41,43] However, when individual peak linear and angular accelerations were assessed, moderate 2-handed slashing to the side of an unhelmeted headform and all severe 2-handed slashes to the unhelmeted headform produced angular accelerations within the ranges reported for concussion.[14,25,27,30,32,33,41,43] In addition, follow-through slashing produced mean and individual peak linear and angular accelerations at levels associated with concussion.[14,25,27,30,32,33,41,43] These findings are consistent with those of Caswell et al,[2] who reported most head injuries were a result of being unintentionally struck in the head by a stick while defending a shot. These findings reinforce the importance of enforcing proper stick checking technique and rules to limit impacts from high-velocity player-to-stick contact.

The linear and rotational accelerations produced by stick impacts in this study were lower than other swing instruments impacting a headform. Coulson et al[3] found that slashing a helmeted headform to the center of the forehead with a wooden laminate hockey stick produced mean linear and angular acceleration of 138*g* and 14,100 rad/s^2, respectively. However, Coulson et al used male hockey players who struck a helmeted headform with maximal effort. When impacting an unhelmeted headform with a wood and aluminum baseball bat, it was found that females produced smaller peak linear and angular acceleration than males (S. de Grau and T. B. Hoshizaki, unpublished data, 2014). A female who swung an aluminum bat 1-handed produced peak linear and angular accelerations of 119*g* and 12,320 rad/s^2, respectively, for side impact to an unhelmeted headform, whereas she produced peak linear and angular accelerations of 132*g* and 13,247 rad/s^2, respectively, when swinging an aluminum bat with 2 hands. Such accelerations are comparable with the highest individual peak linear and angular accelerations produced by follow-through slashing using lacrosse sticks for side impacts (128*g* and 15,199 rad/s^2, respectively). Follow-through slashes have the potential to produce linear and angular accelerations similar to a baseball swing. However, the mean peak linear and angular accelerations are considerably lower. Such variances in linear and angular accelerations reported for

lacrosse stick impacts research studies are likely due to differences in effective impact mass and inbound velocity.

The influence of increasing velocity and mass has been documented to increase the magnitude of the dynamic response incurred from an impact.[19,34,36,37] Lacrosse sticks, hockey sticks, and aluminum bats all have different mass and therefore different striking masses. The 5 lacrosse slashing techniques, baseball swings, and ice hockey slashing all differ in striking techniques. Striking techniques have been reported to increase effective impact mass in boxing and football and could explain differences among previous research.[38-40] Varying striking mass by 2 kg showed an influence to the head response when the effective striking mass was below 10 kg.[19] Further differences in the risk of concussion among lacrosse slashing techniques and previous research could be a result of different inbound velocities. When impacting ice hockey helmets, both peak linear and angular accelerations were found to increase with increasing velocity.[37] Similar results were also found when impacting a bare headform.[36] Peak linear accelerations were also found to increase with increasing velocity, but peak angular accelerations were similar at 5.5 and 7.5 m/s but increased by approximately 40% for impacts at 9.5 m/s when impacting an American football helmet.[34] A combination of differences in effective mass and inbound velocity is a likely contributor to differences in peak linear and angular accelerations produced by stick impacts in women's lacrosse.

When players accidentally collide, falls were found to produce higher linear and angular accelerations than shoulder impacts. Shoulder impacts did not produce significantly different mean peak linear and angular accelerations than 1-handed and 2-handed slashing. Consequently, shoulder impacts produced peak linear and angular accelerations below reported ranges of concussion.[14,25,27,30,32,33,41,43] Caswell et al[2] observed that in 3 of the 4 cases of body contact, a secondary impact of head to ground may have contributed to concussive events. In this study, falls were found to produce significantly higher peak linear and angular accelerations than shoulder impacts. When impacting an unhelmeted headform, falls produced peak linear accelerations within the range of concussion and traumatic brain injury (TBI).[‡] It would appear that when players collide, high peak linear and angular accelerations may be a result of contact with the ground rather than contact with another player.

Ball impacts were found to produce significantly higher peak linear and angular accelerations than all stick impacts except for angular acceleration compared with follow-through slashing. In addition, ball impacts to an unhelmeted headform produced peak linear and angular accelerations within previously reported concussion ranges.[14,25,27,30,32,33,41,43] Such findings would agree with previous epidemiology studies that report player-to-ball contact to be a mechanism of concussion in women's lacrosse.[2,6,7,18,23,24,28] High linear and angular accelerations from a projected lacrosse ball are inconsistent with other projectiles to an unhelmeted headform. Rousseau et al[35] struck a bare and helmeted headform with a puck at 17, 23, 29, 35, and 41 m/s and found that puck impacts to a bare headform at 17 m/s produced peak linear and peak angular accelerations of 138*g* and 13.3 krad/s^2, respectively.

Given that high linear and angular accelerations are associated with high-velocity stick impacts, falls, and ball impacts, the current rules and coaching could produce a game that minimizes these impacts. Such major fouls as the rough/dangerous check, check to the head, slash, obstruction of the free space to goal (shooting space), illegal shot, and dangerous follow-through must be strictly enforced to protect players against accidents resulting in concussions. However, research has reported that in nearly all cases of head injury, no penalty was called.[2] In addition, players lack the ability to self-monitor the location of their stick relative to other players[7] and position themselves in hazardous situations, either purposely or inadvertently.[2]

These results demonstrated men's lacrosse helmets are effective in reducing linear and angular accelerations in women's field lacrosse. They support previous research suggesting if helmets were worn in women's lacrosse, it could decrease the rate of concussion.[6,23,28] Men's lacrosse helmets did not prove to significantly decrease accelerations experienced by the headform in all conditions. However, this occurred in stick impacts and shoulder collisions conditions, which produced very low linear and angular accelerations. In all unhelmeted conditions that resulted in peak linear and angular accelerations within the range of concussion,[14,25,27,30,32,33,41,43] men's lacrosse helmets significantly lowered the accelerations experienced by the headform. Furthermore, the men's lacrosse helmet managed to maintain peak linear and angular accelerations below reported concussion values,[14,25,27,30,32,33,41,43] except in cases where falls produced accelerations approaching TBI thresholds.[1,9-11] In such cases, accelerations decreased to levels within the ranges reported for concussions,[14,25,27,30,32,33,41,43] demonstrating men's lacrosse helmets could provide an effective method to manage linear and angular accelerations in women's lacrosse.

The effect of helmets decreasing the accelerations experienced by the head has also been shown in previous research.[36,37] Rousseau et al[35] found peak linear and acceleration were significantly reduced for puck impacts at 17, 23, 29, 35 and 41 m/s when comparing a helmeted headform to a bare headform. At 5 m/s, peak linear and angular accelerations were significantly lower for impacts to a helmeted headform compared with unhelmeted headform impacts.[36] If playing rules are not properly followed and enforced, then men's lacrosse helmets provide an alternative solution to decrease the linear and angular accelerations experienced in women's field lacrosse.

Limitations

The results presented in this study are specific to men's lacrosse helmets and do not represent ability of soft headgear to reduce linear and angular acceleration of a headform. Current American Society for Testing and Materials (ASTM) development has proposed a standard

[‡]References 1, 9-11, 14, 25, 27, 30, 32, 33, 41, 43.

for woman's lacrosse headgear (ASTM F08.51). In the event the standard is accepted, a future study should assess the ability of certificated women's lacrosse headgear to reduce the dynamic impact response for different striking techniques in women's field lacrosse. The range of linear and angular accelerations used to represent concussion is based on reconstructions of a wide variety of sporting and everyday accidents[14,25,27,30,32,33,41,43] and may not accurately reflect concussion in women's field lacrosse. The Hybrid III headform, despite being widely accepted and used as a human head surrogate, is not biofidelic and will not imitate the dynamic properties of a human head. Furthermore, a 50th percentile Hybrid III adult headform was used because it was available in the laboratory. This headform is specific to the average head size of the population, which may not represent the response of an average female head size under the same impact conditions. A smaller Hybrid III 5th Percentile headform was developed by First Technology Safety Systems. The differences in these 2 headforms would produce characteristic dynamic responses to impact, but the relationship between the impact parameters and the headform response is assumed to be similar for both models. Peak resultant accelerations do not account for acceleration curve characteristics and therefore may not accurately predict brain injury.[31] The use of finite element modeling to assess the risk of concussion could be of benefit as it allows for the interpretation of linear and angular loading curves and how they influence the response of neural tissue. Finally, participants had to focus on impacting the target at the desired locations. The results presented in this study represent conservative values as participants reported a trade-off between speed and accuracy.

CONCLUSION

One-handed slashing, 2-handed slashing, and shoulder impacts were found to be associated with low linear and angular accelerations. However, falls, ball impacts, and high-velocity stick impacts are associated with high linear and angular accelerations. A men's lacrosse helmet proved to be an effective method of reducing the linear and angular accelerations experienced by the headform for these types of striking. Thus, women's field lacrosse can decrease the occurrence of high linear and angular acceleration impacts by having governing bodies improving rules, implementing the use of helmets, or both.

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